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Smart Industrial Metabolism: a literature review and future directions

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Abstract

Corporate and academic interest in the concept of industrial metabolism has risen considerably in recent years. This can be observed in the number of papers published. In order to go deep into current and future trends in this field, the paper objective is multiple. Firstly, the purpose of this paper is to carry out a literature review on industrial metabolism. Secondly, this paper offers a summary of the research in this field, performing a descriptive analysis based on identifying temporal distribution of publications, journals in which papers are published and classifying different applications of industrial metabolism concept. Thus, this paper seeks to provide a review of the main approaches to industrial metabolism. Finally, an overview of immense opportunities for the implementation of industrial metabolism based on Industry 4.0 is presented.

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Keywords: Smart Industrial Metabolism; Sustainable manufacture; Industry 4.0; Metabolism for sustainable manufacturing

1. Introduction

In analogy with the biological and physiological notion of metabolism, the concept used in the study of the relationship between society and nature describes and quantifies the flows of matter and energy that are exchanged

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between particular and concrete social conglomerates and the environment (ecosystems, landscape, etc.). This concept has been called social metabolism, socioeconomic metabolism or industrial metabolism (IM) [1].

The previous situation determines the interest in the form of appropriation and use of the natural resources by the societies as metabolism processes between society and nature. Thus, structures, dynamics, capacities and thresholds of the ecosystems must be considered [2], which constitute the material basis of production, i.e. metabolism.

An important different between biological and artificial systems is that biological systems are efficient by themselves in the use of energy and resources, however industrial systems must be managed to achieve this efficiency. Thus, practical implementation of ecological concepts is not exempt from difficulties [3]. Relationships and interactions between companies, environmental impacts, lack of confidence, deficiencies in transmission and lack of reliability of information and the need for gradual implementation are some of these obstacles.

The aim of this paper is to carry out a brief literature review about IM, identifying the relationship with other concepts in sustainability. Furthermore, an overview of immense opportunities for the realization of IM based on Industry 4.0 [4] is presented.

This paper is organized as follows. Section 2 presents methodology carried out. Section 3 performs the descriptive analysis about literature review. Section 4 presents the opportunities of IM in Industry 4.0. Finally Section 5 presents the conclusions.

1.1. Basic terminology

To prepare the ground for the revision presented, some key terms are defined. According to the definition of IM presented by Wernik [5], "Industrial metabolism considers human societies as systems for transforming materials by describing the exchange of materials and energy between human society and nature in a way analogous to the description of material and energy balances in natural organisms and ecosystems".

Circular economy is a concept, introduced by David Pearce in 1990, that has its conceptual roots in industrial ecology. This concept pursues to converts open-ended system to a circular system when the relationship among resource use and waste is considered. Applying the first law of thermodynamic, where the planet is seen as a closed system. Thus, circulating matter and energy in the economic system would reduce the quantity of inputs and limit the increasing entropy [6].

2. Methodology

The analysis of documents seeks to concentrate existing research and allows establishing the conceptual content of the study field. This analysis pursues the aim of contributing of theory development.

Proposed methodology allows summarize existing research by identifying patterns and themes. Furthermore, it helps to contribute to theory development and can identify the conceptual content of the field. Process model proposed contains four steps:

- Material collection: The material to be collected is defined and delimitated (research areas like industrial, manufacturing, ecology, sustainability, etc.)
- Descriptive analysis: Formal aspect of the material.
- Category selection: The collected material have to be selected in structural dimensions and related analytic categories.
- Material evaluation: The material is analyzed according to the structural dimensions. This should allow identification of relevant themes and interpretation of results.

2.1. Delimitations of the research

A literature review requires establishing clear boundaries with the aim to delimitate the review. In this paper two considerations were made:

- This review considered only papers in peer-reviewed scientific journals.

- English papers were only considered.

The search was carried out as a structured keyword search, whit the aim to achieve a simpler search. The most relevant databases have been used to search for related publications. Specifically the databases used were: Scopus and Sciencedirect.

Taking this delimitation into account, a total of 714 papers were identified.

In order to classify the papers, a descriptive analysis was carried out. (1) Identification of the temporal distribution of publications, (2) identification of journals in which papers are published, (3) classification of different approaches to IM concept. For this classification, each paper was assigned to one or more categories.

3. Descriptive analysis

3.1. Distribution across the time period and main journals

The totality of the identified literature is composed of 714 papers, analyzing in all fields the IM concept in searching. Then the search has been refined including only papers containing the IM concept in the fields Article title, Abstract and Keywords, obtaining a total of 86 papers. The distribution of both searches is included in the period analyzed from 2002 to 2016 (15 years), as it can be seen in the Fig. 1.

Although the term was introduced by Ayres [1] in 1994, to know the current state in this field the last 15 years have been taken in account. A large number of papers are found in this period, mainly in the period between 2012 and 2016. It significantly increased in recent years 2014 and 2016. This shows, in a special way, the acceptance of this topic among research. However this term is linked, and sometimes appears mixed, with the concepts of social metabolism and urban metabolism.

Based on the main search, there is an uneven distribution among number of papers as a function of the journal. Thus, the leader regarding the number of publications is Journal of Industrial Ecology with 65 papers, followed Journal of Cleaner Production accounts for 56 papers. Followed by previous appears Ecological Economics with 32 papers, Resources, Conservation and Recycling with 29 and Progress in Industrial Ecology with 21 papers.

With regard to refined search, there is homogeneous distribution among number of papers as a function of the journal. Thus, the distribution regarding the number of publications is Journal of Industrial Ecology (15), Journal of Cleaner Production (10), Progress in Industrial Ecology (8), Ecological Economics (6), and Ecological Economics and Resources, Conservation and Recycling (6).

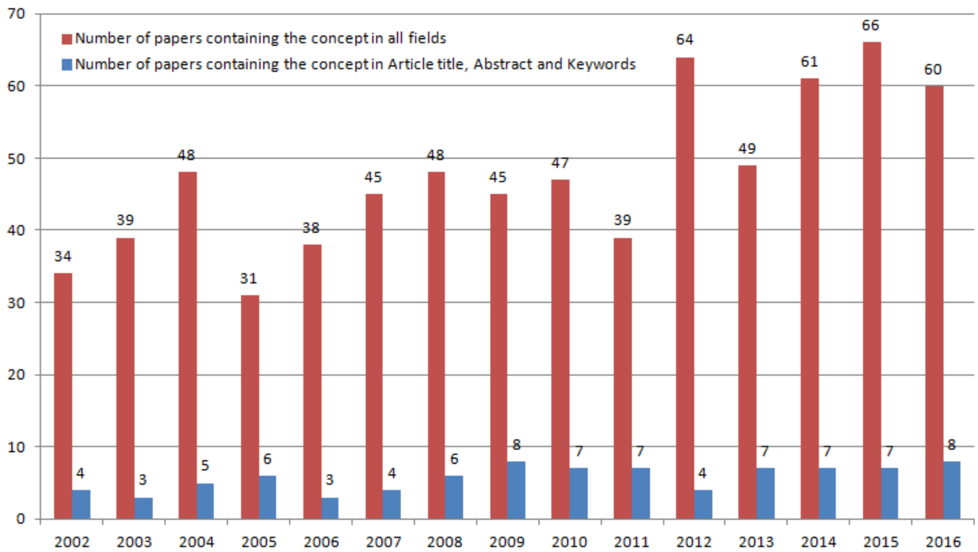

Fig. 1. Distribution of publications per year across the period studied.

Four research methodologies have been differentiated: literature review, theoretical and conceptual, case study and modelling. Table 1 shows the assignments of the paper to the research methodology.

Table 1. Assignments of the papers to the research methodology.

Research methodology	All fields (86 papers)	Article title, abstract and keywords (86 papers)
Literature review	25	6
Theoretical and conceptual	493	10
Case study	116	51
Modelling	183	25

3.2. Biological analogy

In the field of biology, metabolism it is understood as the set of biochemical reactions that take place in a living cell level or body. However, this processing substance need not take place exclusively at the cell level. The definition of metabolism can be extended beyond the processes of cell anabolism and catabolism, including materials and energy flows occurring at different functional levels of living systems [7]. While biology develops knowledge of metabolism at the individual level, industrial ecology has led to expand this analogy to the level of industrial ecosystem. So it is possible to study the metabolism of industrial ecosystem.

IM is also defined as the use of materials and energy flowing through industrial systems for processing and later his disposal as waste. It is aimed at understanding the movement of material flows, water and energy (and stocks) linked to human activity, from their extraction to their inevitable reintegration in global biogeochemical cycles, or technical cycles in the technosphere [1]. In this analogy, which incorporates biological metabolism enzymes that catalyze biochemical reactions, metabolic processes associated to industrial manufacturing, distribution, use, logistics and end of life, are composed of resources, machines or workstations that provide added value the input material, and considering the same processes anabolism and catabolism, called metabolic steps.

Others contributions considering IM from a biological analogy view in industrial ecology to social metabolism approach [7]. Such approaches based on manufacturing cells and trophic chain, classifying agents involve in manufacturing systems as producer (autotroph), consumer (heterotrophy), industrial energy producer (energy), and industrial decomposers as enterprises aiming at transforming, recycling, and neutralizing by-products (decomposers) [8].

IM (in relation to the network and flows between nodes) can provide a basis for the optimization of processes and improvement of environmental and economic performance. Thus, other approaches are oriented to metabolic networks [9]. In addition, the studies evolve since its consideration at the ecosystem level and its analogy in the implementation in industrial eco-parks to cases of use of IM application in eco-industrial parks [10].

3.3. Circular Economy

Circular economy concept is applied to analyzer industrial systems, based on IM, leading them to a new model of economic development, production, distribution and recovery of products. However, circular economy implementations appear to be still in the early stages, where its main objective is to recycle rather than reuse. Circular economy involves the adoption of sustainable standards at company level, an increase in the responsibility of producers and consumers, the use of renewable technologies, as well as more sustainable, clean and stable policies and tools [11].

Circular economy allows identifying the key potential opportunities for improvement using analysis tools and assessment tools. Its implementation at micro level requires the adoption of eco-design. Eco-design considers all the environmental impacts of a product since its conception; it provides a way to improve the circular economy by obtaining the improvement of resource use. Furthermore, by applying eco-design and decision tools, a firm-level, circular economic system is designed and constructed [12]. At meso level, EIPs initiatives are considered. This initiative adopts the perspective of industrial symbiosis among companies. However, market conditions (price of by-products) difficult to carry out the industrial symbiosis, evidencing that economy perspective may be decisive in ecology perspective. At macro level, there are interesting approaches, as eco-cities, zero waste programs, circular economy indicators, etc [11].

In order to stimulate circular economy implementation, comprehensive knowledge on designing circular business models is needed. Thus, eight sub-domains on circular business models (definitions, components, taxonomies, conceptual models, design methods and tools, adoption factors, evaluation models and change methodologies) can be used to redefine the components of the business model (partners, key activities, key resources, value proposition and customer segments, customer relations, channels, cost structure and revenue streams) in the context of the circular economy [13].

3.4. Eco-Industrial Park (EIP)

In recent years, a growing interest in the use and implementation of IM concept at EIP level is being appreciated. Industrial parks are used, in the current socio-economic model, to concentrate industrial activity in a specific area for economic purposes, sometimes proving contradictory from the point of view of environmental protection. Thus, EIP can be considered as an adequate way to builds IM concept for the analysis of industrial systems [11]. Here, IM can provide an adequate basis for optimizing processes and improving environmental and economic performance [9].However, its real and complete implementation is not free of difficulties. Most of papers analyzed are focused on the search for indicators, index, factors, etc. identifying the strengths and weaknesses of EIP. The conclusions obtained from these studies are intended to support decision making during the life cycle phases of this type of industrial park.

Based on the natural analogy, some research develop index to evaluate an EIP [14]. Thus, these index are oriented to evaluate the connectance of an EIP, defining the level of connectivity among factories in a location; and identifying the level of byproduct reused in an EIP. Some studies, related with chemical industry, are oriented to define a specific metabolic model at EIP level, based on identify the main flow routes of metabolic pattern. This allow to identify the production path and its resource efficiency for the whole park [15]. Other studies are focused to establish the casual relationship of EIP factors. Thus, once relationship among factors has been analyzed, this study suggests that factors regarding resource circulation system development have important impacts on EIP development and cooperative system development. The identification of these relationship of development factors facilitates the make decision in the development of strategies [16].

The identified key success and limiting factors are: the creation of symbiotic relationship, information sharing and awareness, financial benefits, organizational structure, and legal and regulatory framework.

In specific areas, as cooper industry, general models based on IM are developed. Han [17] proposes six indices to quantify and evaluate copper and sulfur metabolisms as well as the economic performance of the system. These indices are: resource utilization efficiency, production efficiency, reuse efficiency, system loss rate, environmental factor and resource productivity.

Other important perspective of IM at EIP level is to identify the metabolic paths, analyzing internal characteristics if metabolism processes taking in account their structural and functional attributes [18]. By using network analysis, it is possible to identifier nodes, paths, flow quantity and directions, etc. Thus, key node and paths can be identifying, and improving the efficiency and the sustainable development of EIP.

4. Industry 4.0 for implementing IM

The introduction of the Internet of Things into the manufacturing systems is developing a fourth industrial revolution. In the near future, industries will establish networks that incorporate their process, products, machinery, warehousing systems, supply chain in the shape of cyber-physical systems. The Industry 4.0 initiative has huge potential in meeting individual customer requirements, flexibility, optimizing decision-taking, resource productivity and efficiency, creating value opportunities through new services, responding to demographic change in the workplace, work-life-balance and a high-wage economy that is still competitive [19].

In the manufacturing environment, industry 4.0 requires the implementation of the following features: horizontal integration through value networks, end-to-end digital integration of engineering across the entire value chain and vertical integration and networked manufacturing system. Thus, to achieve IM, Industry 4.0 can be used to allow its implementation. Thus, the actual situation of lack of real implementation can be directed through the incorporation of digital technologies [20]: Internet of Things, Cloud computing, Big Data, embedded computing, ubiquitous technologies [21], etc. In line with this, the necessity to evolve from IM to smart IM is appreciated.

5. Conclusions

This paper has taken a broad look at IM, the issues emerging in this field, and its different approaches to IM concept. It offers a conceptualization based on literature review, from its implementation based on direct biological analogy to the implementation with other concepts. This concept provides significant advantages over the current management of industrial systems that lack a global view. It is clear from the analysis that the correct and efficient application of indices, factors, data collection, inputs/outputs, etc. requires systems for the acquisition of data in real time. The incorporation of Industry 4.0 and its opportunities allows decreasing time management, ensure anonymity among organizations involved in the exchange process, while establishing a shared informational system that facilitates the identification, analysis and closing the resources cycle.

References

[1] R.U. Ayres, Industrial Metabolism: Restructuring for Sustainable Development, U.N.U. Press, 1994.
[2] M. González de Molina, V. Toledo, The Social Metabolism - A Socio-Ecological Theory of Historical Change, Springer, 2014.
[3] F. Pomponi, A. Moncaster, J. Cleaner Production, 143 (2016) 710-718.
[4] T. Stock, G. Seliger, Procedia CIRP, 40 (2016) 536-541.
[5] K. Wernick, Industrial Metabolism. International Encyclopedia of the Social & Behavioral Sciences, 2001, pp 7331-7333
[6] M.S. Andersen. Sustainability Sci., 2 (1) (2007) 133-140.
[7] T. Wassenaar, J. Industrial Ecology, 19 (5) (2015) 715-727.
[8] E. Liwarska-Bizukojc, J. Cleaner Production, 17 (8) (2009) 732-741.
[9] Y. Fan, Q. Qiao, L. Fang, J. Cleaner Production, 142 (4) (2017) 1552-1561.
[10] Y. Fan, Q. Qiao, L. Fang, Y. Yao, J. Cleaner Production, 141 (2017) 791-798.
[11] P. Ghisellini, C. Cialani, S. Ulgiati, J. Cleaner Production, 114 (2016) 11-32.
[12] S. Ma, S. Hu, D. Chen, B. Zhu, J. Cleaner Production, 87 (2015) 839-849.
[13] M. Lewandowski, Sustainability, 8 (1) (2016) 43.
[14] D. Tiejun, Conserv. Recycl., 54 (7) (2010) 442-448.
[15] L. Ma, S. Zhao, L. Shi, Industrial metabolism of chlorine in a chemical industrial park: the Chinese case. J. Cleaner Production. 112 (2016) 4367-4376.
[16] G.H. Hwang, S.K. Jeong, Y.U. Ban, J. Cleaner Production, 114 (2016) 180-188.
[17] F. Han, F. Yu, Z. Cui, J. Cleaner Production, 133 (2016) 459-466.
[18] Y. Zhang, H. Zheng, Z. Yang, G. Liu, M. Su, J. Cleaner Production, 96 (2014) 126-138.
[19] K. Henning, J. Helbig, A. Hellinger, W. Wahlster, Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Final report of the Industrie 4.0 WG, 2013.
[20] R.F. Babiceanu, R. Seker, Computers in Industry, 81 (2016) 128-137.
[21] T. Yigitcanlar, S.H. Lee, Technological Forecasting and Social Change, 89 (2014) 110-114.